

SUMMARY:

This paper describes the HST Electrical Power System (EPS) for use in the development of HST Battery Augmentation for the Hubble Space Telescope Robotic Servicing and De-orbit Mission (HRSDM).

1.0 INTRODUCTION

HST's six on orbit Nickel Hydrogen batteries have experienced a capacity decline since deployment from a system total of 528 Ah (88Ah nameplate each) to approximately 315 Ah. Battery capacity decline is attributed to calendar and cycle life (>14 years, >76700 cycles) and is expected to continue, resulting in significant impacts to future HST science mission and safemode operations.

A robotic servicing mission is planned to service HST. Due to the complexities of a direct robotic replacement of HST's existing batteries, augmentation of HST's batteries is planned through the robotic installation of HST-external batteries. The augmentation batteries will be contained in a De-orbit Module (DM) attached to the HST Aft Bulkhead (AB) during the HST Robotic Servicing and Deorbit Mission (HRSDM). Power for charging the augmentation batteries will be provided by tapping HST's Solar Array-3 (SA3) together with surplus SA power from the DM. The tapped SA3 power will be conducted to the augmentation batteries by robotically installed HST-external harnesses. The tapped SA3 power will support the HST loads and charge the augmentation batteries during orbit day. The augmentation batteries will support the HST loads during orbit night. Power to support HST's loads will be conducted back to HST's Main and Essential Buses via the servicing mission Main Electrical Umbilical J101.

In order to design a battery augmentation system, an understanding of HST's EPS system is required. This white paper describes the HST EPS and provides critical information required for the development of HST battery augmentation for the HRSDM.

2.0 HST EPS

The HST power loads are sourced by a slewable Solar Array (SA). The on-orbit SA3 replaced SA-II during Servicing Mission 3B on 4 March 2002. HST's EPS uses direct energy transfer of SA3 power to the spacecraft batteries and loads and relies upon its six Nickel Hydrogen batteries for Bus voltage regulation. SA3 provides power to the HST loads and charges the batteries during orbit day. HST's batteries provide power to the HST loads during orbit night.

2.1 SA3:

SA3 is composed of two SA Wings, each of which is slewable to maximize SA3 power output (see Figure 1). Each Wing is composed of 4 SA Panels. Each SA Panel is approximately 46" x 130" and is populated with 10 SA Strings with an output of ~ 2.1A per String (2.5A maximum per string). Each SA String is composed of 2 parallel connected Circuits of 50 series connected Ga-As dual junction solar cells (see Figure 2). The power from the 40 SA Strings on each SA3 wing are redundantly conducted to the respective Diode Box Assembly-2 (DBA2) via 4 power harnesses. The power harnesses, P5A, P6A, P7A, and P8A, are redundant such that 20 strings from a given SA3 wing are provided on P5A and P6A and the remaining 20 strings are provided on P7A and P8A (see Figure 3). Figures 4 and 5 show typical SA3 to DBA2 electrical schematics. Figure 4 shows typical redundant SA3 String harness wiring pre SA3 tapping. Figure 5 shows typical SA3 String harnessing post tapping.



Figure 1, HST With Deployed SA3 Wings Post Servicing Mission 3B

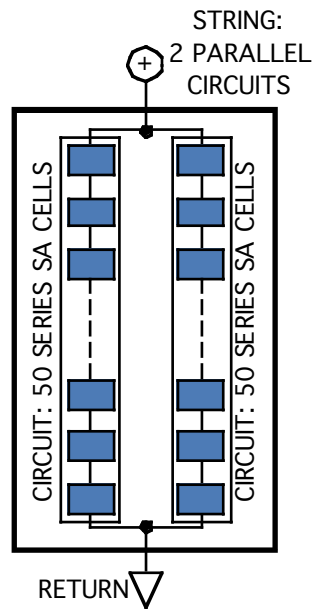


Figure 2, SA3 String Design

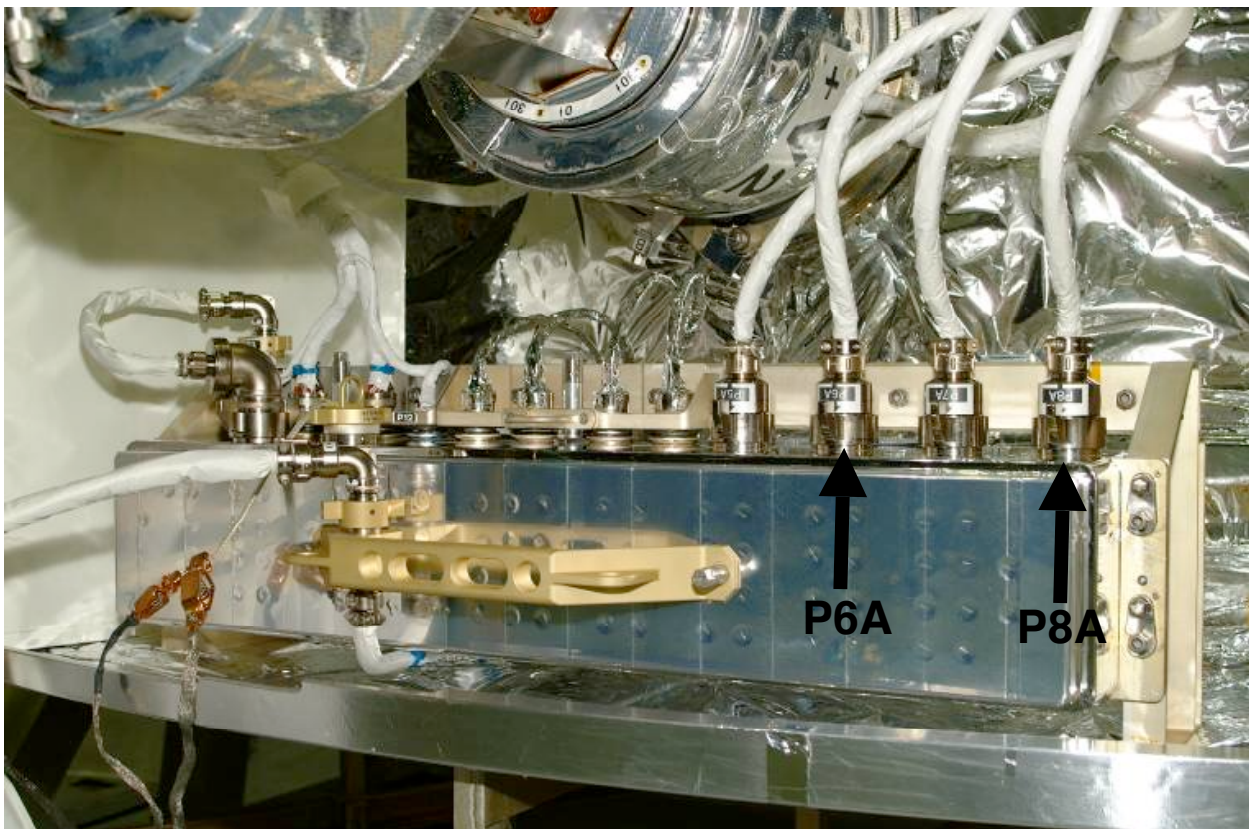


Figure 3, HST DBA2 Mock-up With SA3 Harness Connectors P6A and P8A As Indicated

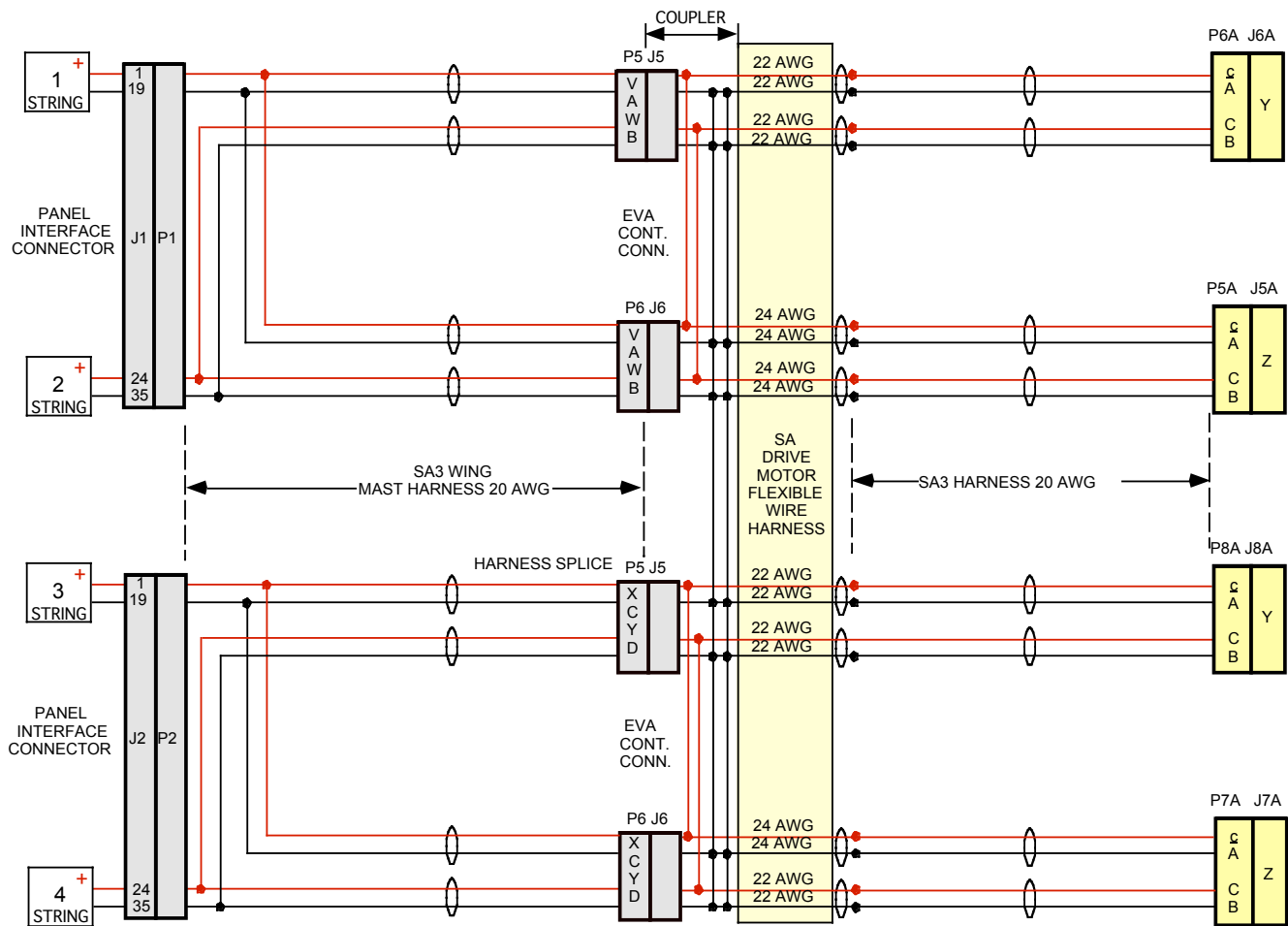


Figure 4, Typical SA3 to DBA2 Redundant Harnessing Schematic Prior to SA3 Tapping

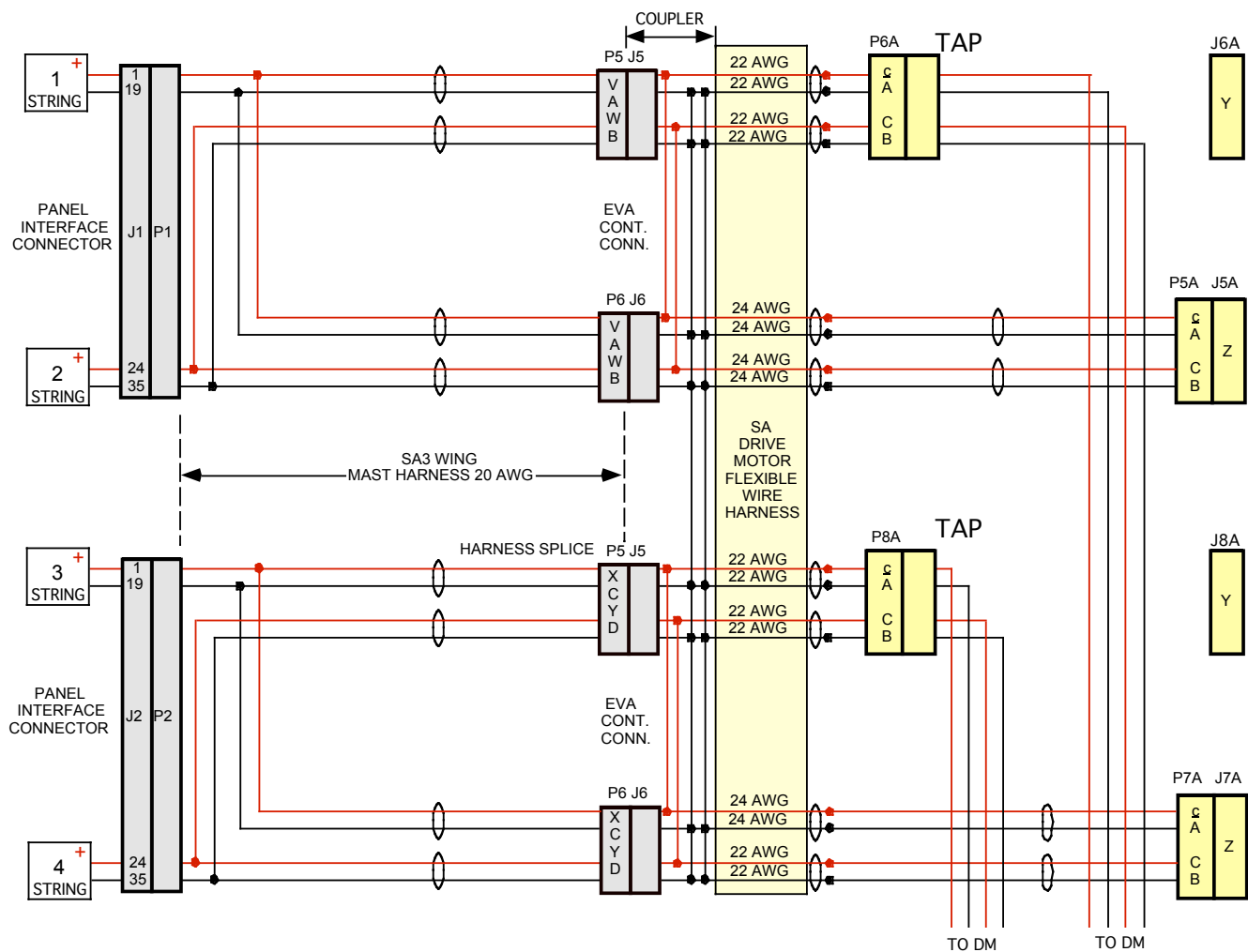


Figure 5, Typical SA3 to DBA2 Redundant Harnessing Schematic Post SA3 Tapping

2.2 DBA2:

The two DBA2s each receive and diode-isolate their complement of 40 Strings. After diode isolation, respective Strings are combined into three 5-String, six 4-String, and one 1-String Solar Panel Assemblies (SPAs). When ground commanded, Disconnect relays in each DBA2 are provided to isolate the hot side of all 10 SPAs simultaneously from the remaining HST EPS. Contingency battery charge control relays are provided in each DBA2. Opening of a charge control relay off-lines the respective SPA. The 1-String SPA in each DBA2 is not provided with a charge control relay. In the event that a charge control relay fails open, all SPA bypass relays, placed in parallel with each charge control relay, can be simultaneously commanded closed to restore the SPA power (see Figure 6). A relay arc suppression circuit is provided in the DBA2 for each SPA to provide relay contact arc suppression protection. Demating at DBA2 P5, P6, P7, or P8 will eliminate arc suppression protection provided by DBA2. The 10 SPAs from each DBA2 are conducted to the Power Control Unit (PCU) via harnessing.

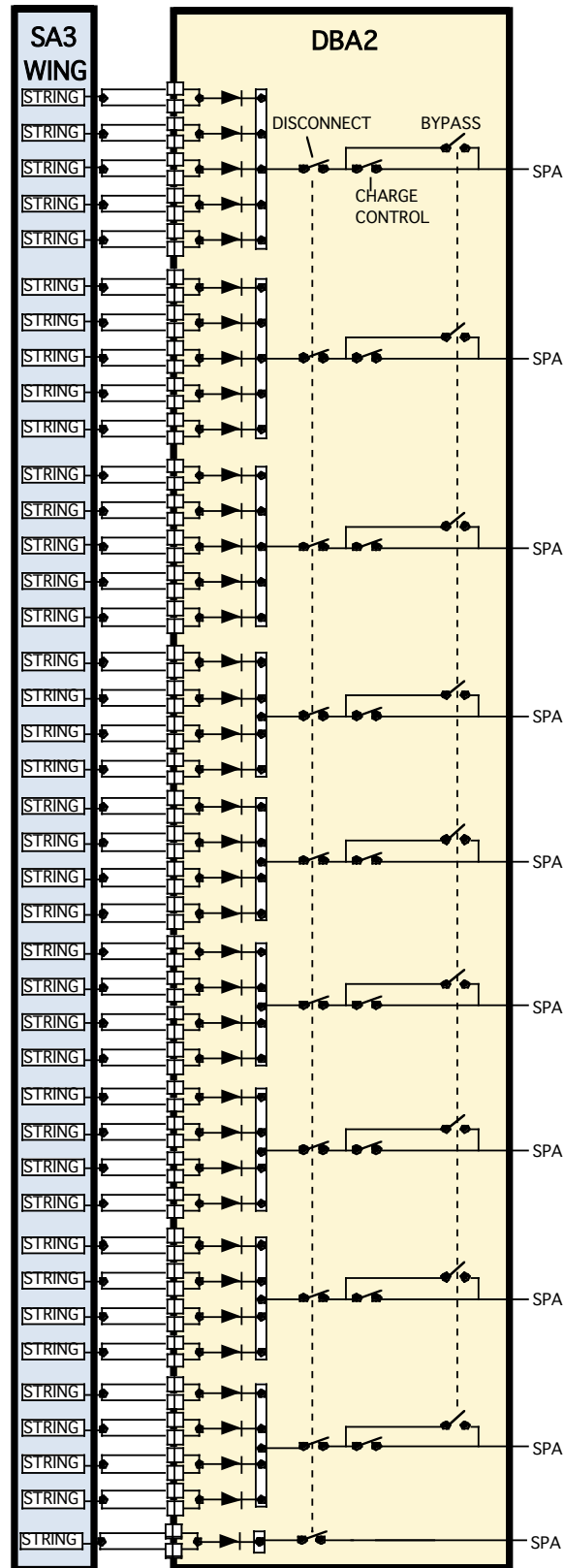


Figure 6: SA3 to DBA2 (arc suppression circuits not shown)

2.3 PCU:

The PCU receives the 20 SA3 SPAs from the two DBA2s and distributes three of the SPAs to each of the six Nickel Hydrogen batteries. Each battery receives one 5-String SPA and two 4-String SPAs. The two remaining 1-String SPAs, rather than being allocated to a battery, are tied to one of three Diode Buses in the PCU.

Primary charge control for each battery is provided by opening the respective Trim relay(s) or Charge Control relay(s) in the PCU. Software battery charge control is provided by opening respective PCU Trim relays based upon battery voltage and temperature data and a software implemented Voltage/Temperature control curve. PCU Charge Control relays are autonomously hardware commanded (Hardware Charge Mode) by dedicated Charge Current Controllers (CCC) external to the PCU which monitor and control battery charging based upon one of four ground selectable Voltage/Temperature curves. There are two sets of 4 V/T curves in each CCC. One set controls the Charge Control relay that switches the two 4-String SPAs; the other set switches the 5-String SPA. Each Trim Relay and respective Charge Control Relay circuit group is provided with a parallel Bypass Relay for ground commanding closed in the event that the Trim Relay or Charge Control Relay fails open.

Each of the six batteries and its dedicated SA3 SPAs are referred to as a Section. Section 7 is formed from the two one-String SPAs and is directed to one of the Diode Buses. Sections 1 and 2 are diode isolated and combined to form Diode Bus A (DBA). Sections 3 and 4 are diode isolated and combined to form Diode Bus B (DBB). Sections 5 and 6 are diode isolated and combined to form Diode Bus C (DBC).

The three Diode Buses are normally interconnected with motor driven transfer switches. The interconnected Diode Buses are also interconnected with motor driven transfer switches to three Main Buses: A, B, and C. For normal operations, Main Buses A (MBA) and B (MBB) are powered. Main Bus C (MBC) is normally unpowered. In the event of an over-current, structure current short, or PSEA Hardware Safemode entry, the three interconnected Diode Buses are autonomously separated and Main Bus C is powered by reconfiguration of the motor transfer switches in an attempt to isolate bus shorts. Main Bus feeds are fused at 35A and are output to four Power Distribution Units (PDU) external to the PCU.

Essential Buses for supplying Multi Access (MA) communication transponder and Command Decoder Interface (CDI) power are provided by diode isolated and 3A fused power feeds from each Diode Bus.

External HST power is input to the Servicing Mission J101 Umbilical. From the J101 Umbilical, Main External power is diode isolated in the PCU and provided to Main Bus A and B only. External Essential Bus power is also provided from J101 and is diode isolated in the PCU and provided to the Essential Buses (see Figure 7).

2.4 EPS Operation:

Prior to the start of orbit day, All PCU Trim and Charge Control relays are closed by flight software and the respective battery CCCs since the battery Voltage/Temperatures are below the respective V/T curves. All Bypass Relays are normally open. The six Nickel Hydrogen batteries' State Of Charge (SOC) has been reduced due to supporting the orbit night loads. As the sun illuminates SA3, HST loads are served by the array and the batteries begin to recharge. As each battery reaches full charge

based upon selected V/T curves, PCU Trim Relays and/or Charge Control relays are opened by flight software and/or the CCCs (software vs hardware charge control). Relays continue to open until the sum of all battery charge currents is less than a database limit or CCC V/T curve thresholds placing each battery in trickle charge during the remainder of orbit day. SA3 continues to source the loads during the remainder of orbit day while trickle charging the batteries. At the start of orbit night, the batteries pick-up the loads as SA3 output power drops to zero. The PCU Trim relays and Charge Control relays are again closed by flight software and the CCCs in preparation of the next orbit day battery charge period. (Note: the DBA2 Charge Control relays are not currently used for battery charge control.)

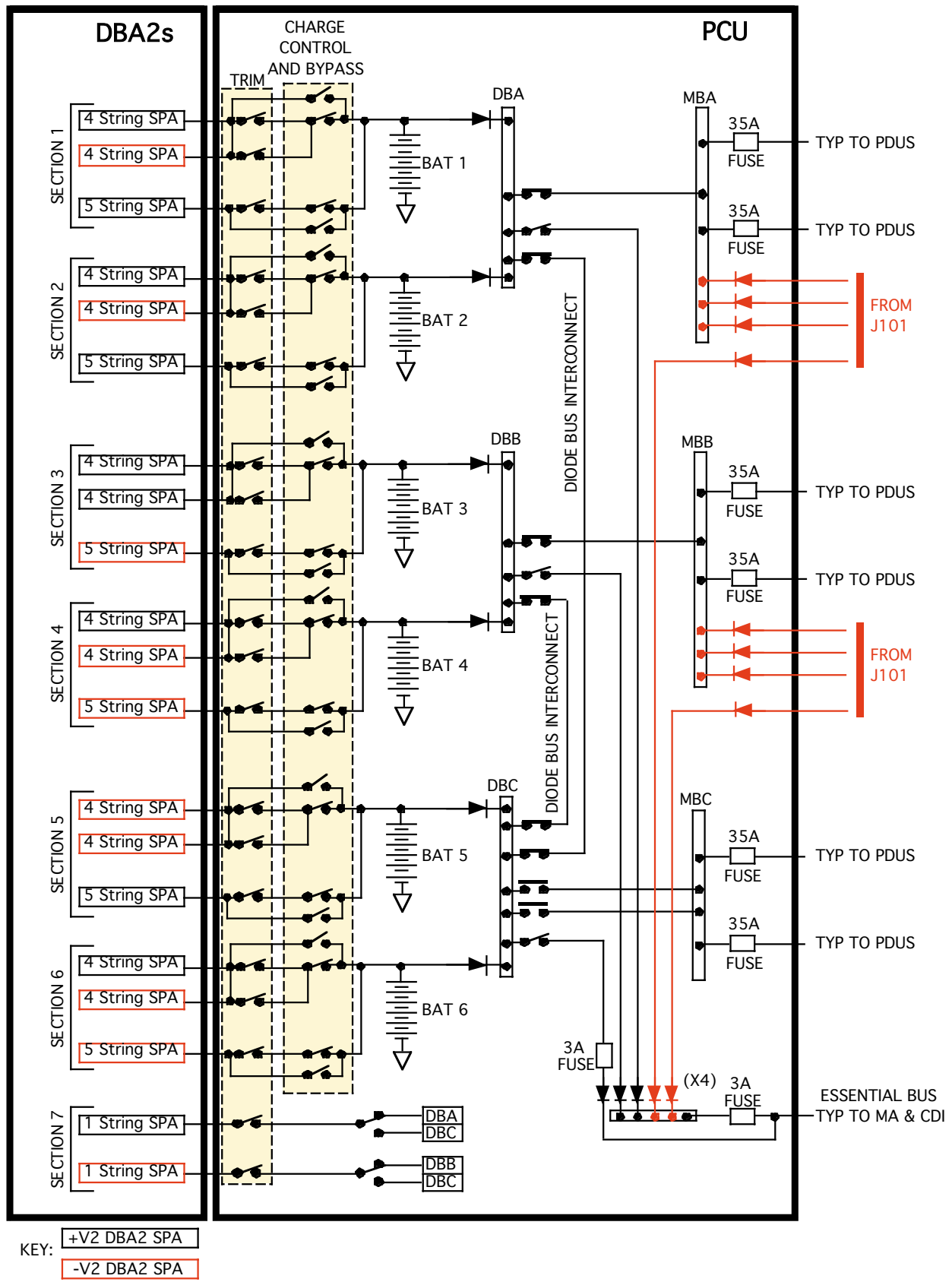


Figure 7: DBA2 to PCU (PCU Returns Not Shown)

3.0 Battery Augmentation

3.1 SA3 Taps

External HST battery augmentation requires robotically tapping into the SA3 wing P6A and P8A harness connectors on each DBA2. The P6A and P8A connectors were selected due to the slightly lower harness voltage drops (due to larger wire size) from the SA3 Panel connectors to the DBA2 connectors. The GFE supplied harness from the P6A and P8A connector taps to the DM SA3 input external interface will be designed to minimize voltage drops. The design for the SA3 tap harnesses will utilize one 12 AWG twisted wire pair per SA3 String.

The DM shall provide reverse current isolation protection at the String level, since the SA3 tap is physically located upstream of the existing SA3 isolation diodes, and the solar cells should not be subject to reverse current when they are not illuminated. The voltage drop from the DM SA3 input external interface to the DM batteries should be minimized to reduce insertion losses and prevent the SA3 from operating significantly beyond its peak power point at the SA3 worst-case hot temperature of +76C. The SA3 String-level I/V curves enveloping best-case and worst-case orbital performance at science mission End Of Life (EOL) at the DM SA3 power interface are given in Figure 8. Figure 8 assumes 170 milliohms of insertion loss (at a wire temperature of 20 Celsius) between the SA3 tap and the DM SA3 power interface.

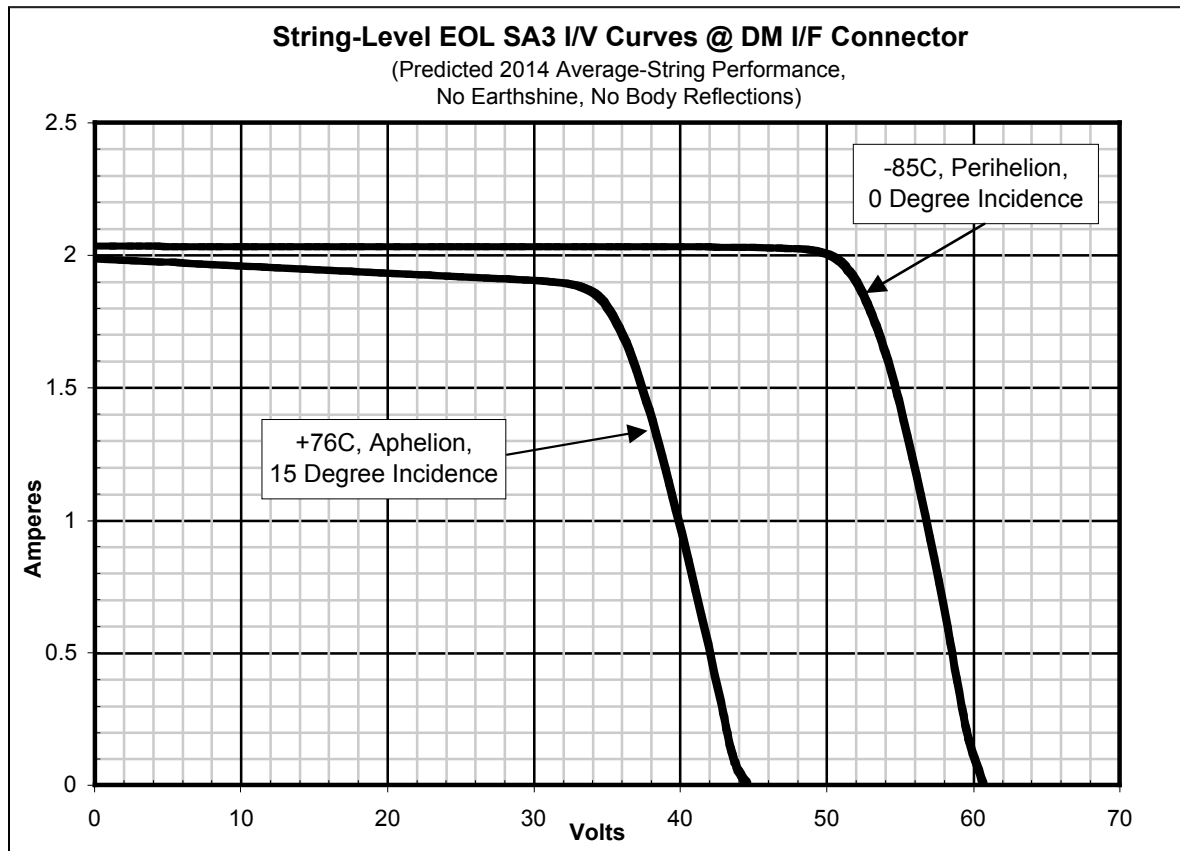


Figure 8, SA3 EOL I/V Curve, Conditions As Stated

3.2 J101 Power Input

The DM shall provide the SA3/battery augmentation power to the HST J101 Umbilical (see Figures 9, 10, 11 and 12). The DM P101 Plug and mechanized umbilical mating equipment will be provided as GFE. Connector and contact information for J101 and P101 is defined in the HRV Requirements document, NNG0461779R (HRVDM), Attachment B.

3.3 P105 and P106 Deployment Umbilical Power Input Contingency

In the event that the P101 Plug fails to mate to the HST J101 Umbilical, the DM shall provide the above power at the HST P105 and P106 Deployment Umbilicals (see Figures 9 and 10). Connector and contact information for P105 and 106 are contained in the HRV Requirements Document, NNG0461779R (HRVDM), Attachment B.

3.4 External Power Regulation

Due to the significant harness losses and diode voltage drops between J101 or P105 and P106 to the HST Main Bus, the HST bus voltage cannot be easily maintained within limits over the full range of battery voltage and load current with a simple direct energy transfer system in the DM; HST is at potential risk of a bus over-voltage with a low load current and high battery state-of-charge, and a bus under-voltage with a high load current and low battery state-of-charge. Therefore some form of input

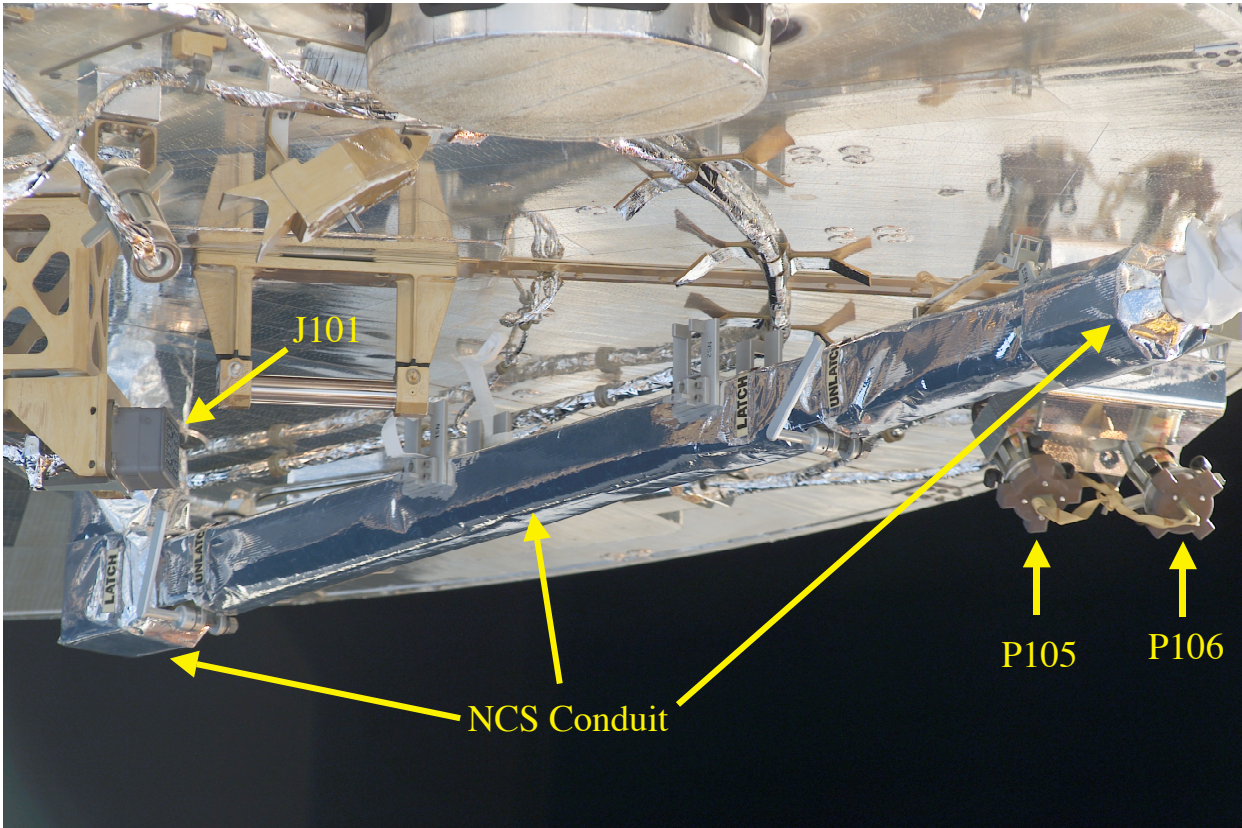
voltage regulation is most likely required. The J101 and P105 and P106 harnesses to the PCU Main and Essential buses are shown schematically in Figures 11 and 12, respectively. An Engineering evaluation of the flight umbilical harness losses and diode voltage drops for the J101 main bus feed is illustrated in Figure 13. The voltage drop through the contingency P105 and P106 would be slightly less because the harnesses are shorter. Figure 14 shows the effect of the losses on HST Main Bus voltage as a function of load current and battery state-of-charge for a simple direct energy transfer system (note that Figure 14 assumes a hypothetical battery, with a 7.2 volt spread between 100% SOC and 0% SOC, at open-circuit).

To maintain the HST bus voltage within the normal operational limits of 26.5 to 32.7 volts, the applied power to the HST J101 or P105 and P106 interfaces shall be as follows: 29.2 VDC minimum @ 105A (peak HST load), 33.5 VDC maximum @ Open-Circuit (zero HST load). Input voltage regulation set closer to the high-end of the allowable range (33.5 VDC) is preferred to reduce the current required to serve the load and thus reduce losses. Voltage regulation can be accommodated by remote sensing through J101 or P106 monitor sense lines (Main Power ON Monitor and Ext Main Power ON Monitor; refer to Figure 11). Maximum orbit average power to support HST loads is ~2500 Watts (supports 3 Science Instrument operations with NCS at maximum power).

The HST Essential Bus feed, serving approximately 1.8 amps peak, is not subject to the high voltage drop that the Main bus feed experiences under high load. This inherent difference in the voltage drop between the Essential and Main feeds must be accounted for in the DM design. Depending on DM implementation, this may require the Essential Bus source to be at a lower voltage than the HST Main Bus source at high load, as the Main Bus source may rise considerably under high load to compensate for the harness drop.

3.4 NCS Power Input

The DM shall provide up to 460 Watts of power to the DM external NCS Diode Box J1 power interface. The 460 Watts is included in the HST required 2500 Watt maximum orbit average power. The robotically installed power harness from the DM external interface to the NCS Diode Box J1 connector will be GFE.



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Figure 9, HST Aft Bulkhead (AB) with J101 and Capped P105 and P106 Interfaces

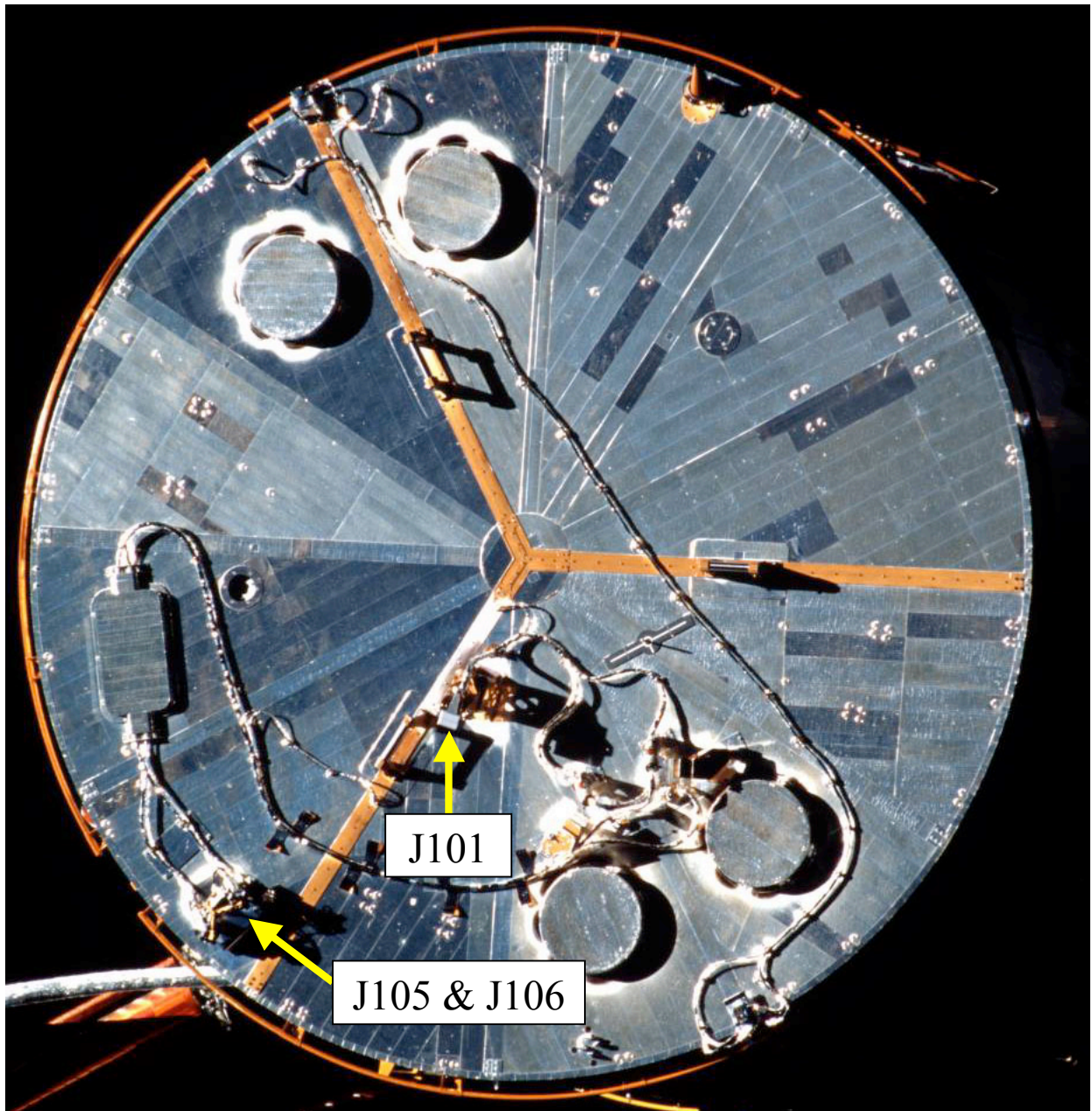


Figure 10, HST AB with J101 and Capped P105 and P106 Interfaces (NCS Conduit Not Shown)

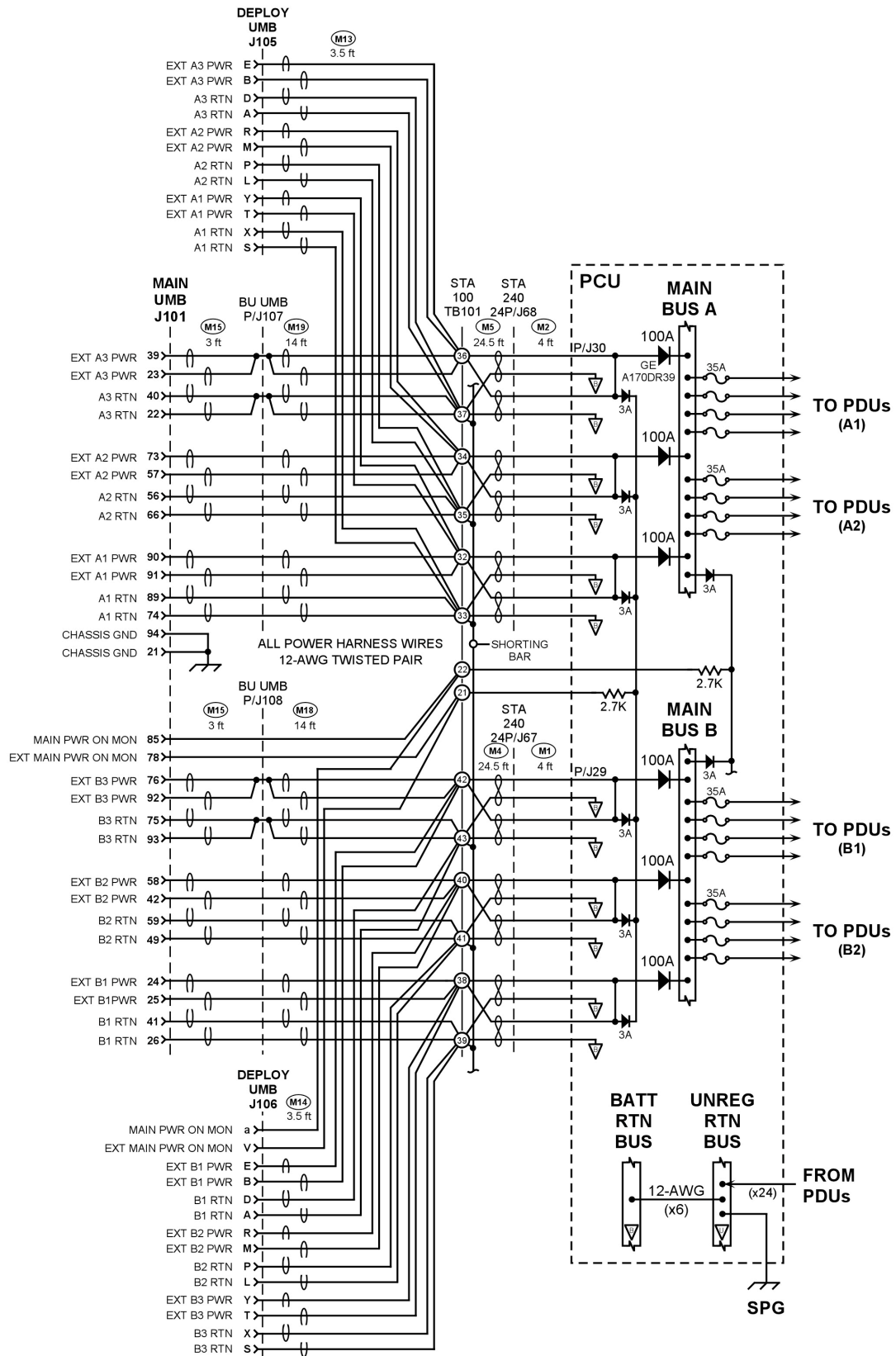


Figure 11, HST Umbilical Harness Main Bus Feed Wiring

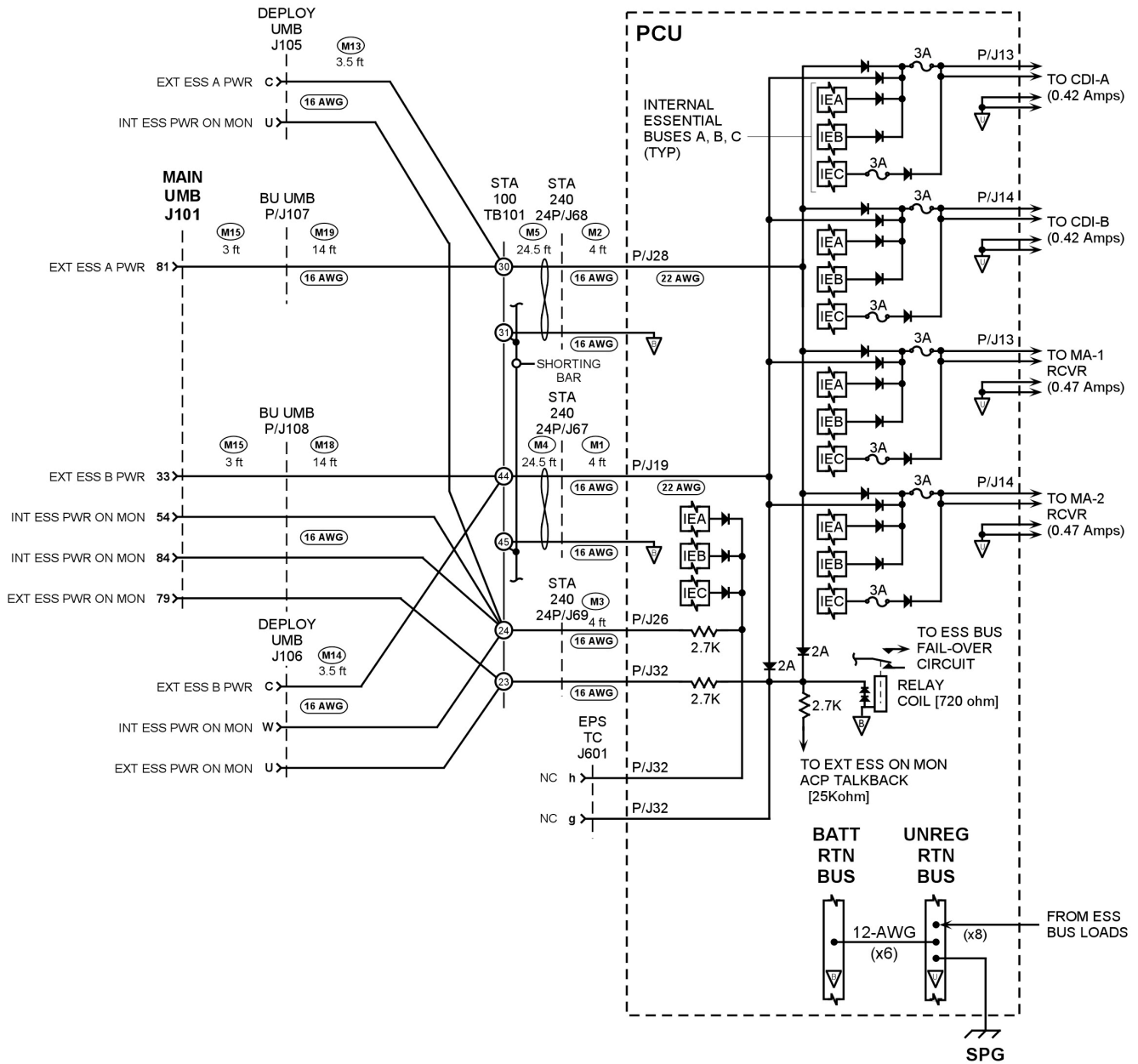


Figure 12, HST Umbilical Harness Essential Bus Feed Wiring

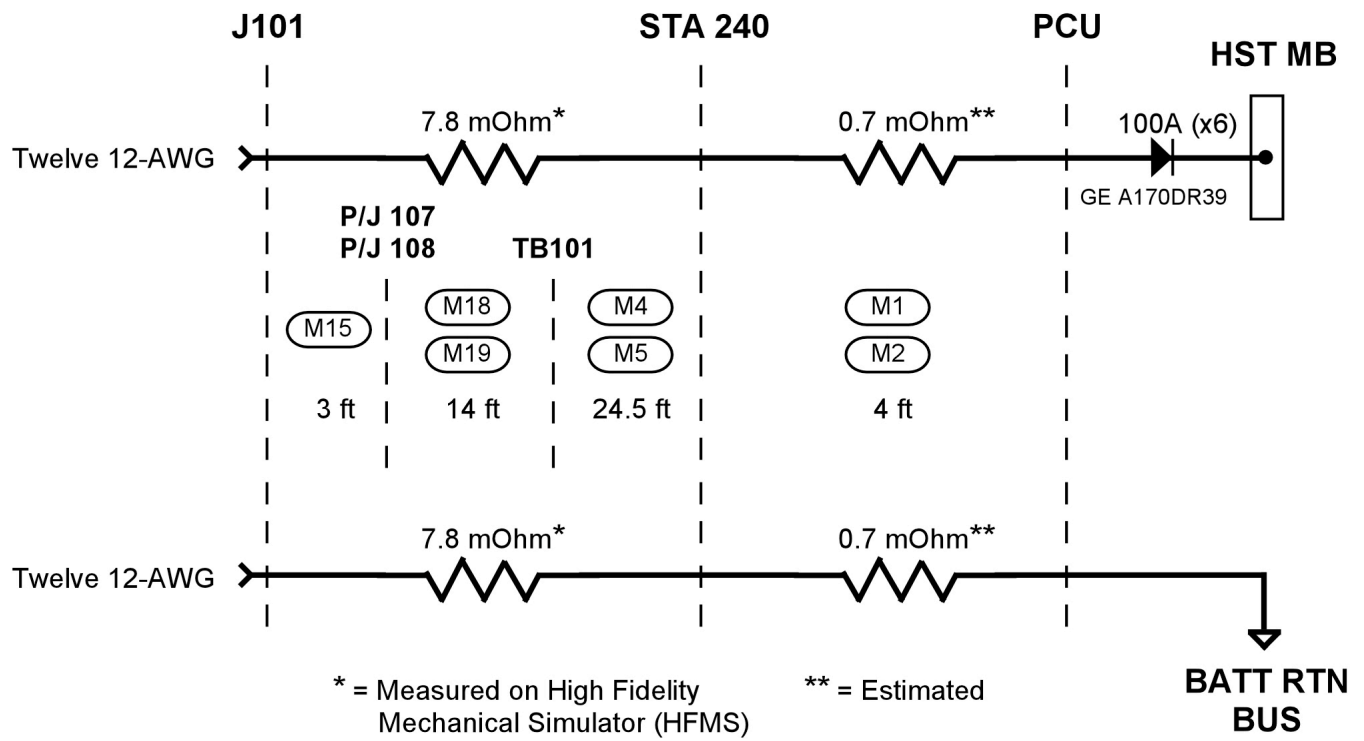


Figure 13, HST Umbilical Harness Characteristics (Main Power)

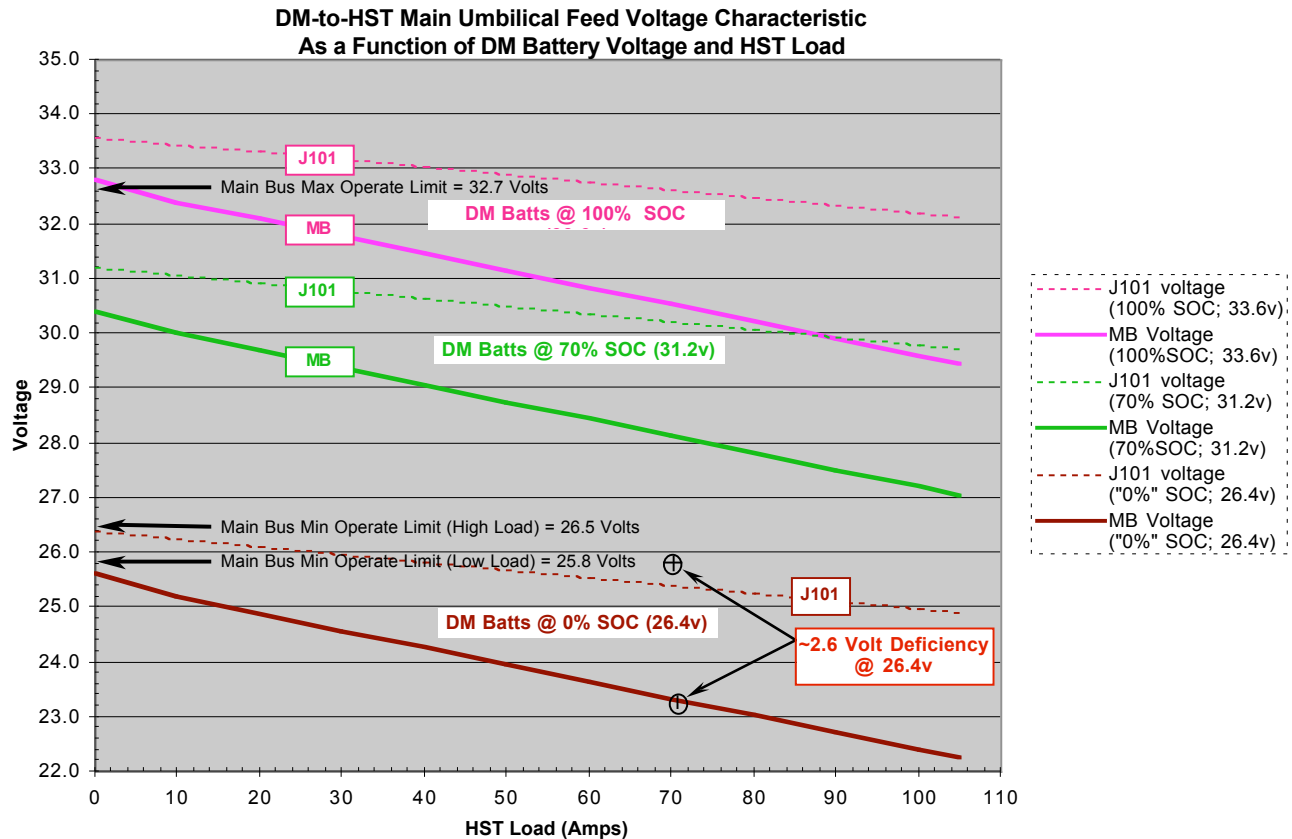


Figure 14, DM-to-HST J101 Umbilical Feed Voltage Characteristic

3.5 Augmentation Operations:

At the time of HRSDM, if the HST batteries have useful capacity, it may be possible to operate HST's EPS in parallel with DM battery augmentation. In this "Hybrid" mode, SA3 would charge the HST batteries and DM batteries until full charge is reached in each respective system while also supporting HST's orbit day loads. Orbit night loads would be sourced by the HST and DM batteries. In the event that HST's battery capacity is too low for science operations, the HST Project may elect to disable HST's EPS by opening the DBA2 Disconnect relays or robotically demating the remaining SA3 power harnesses and thus operate fully in the "External" mode. In this mode, SA3 is dedicated to sourcing HST's loads and charging the DM batteries together with the DM SA in orbit day. In orbit night, the DM batteries would carry the HST and DM loads.

In the event that no SA3 robotic taps are successful, SA3 will source the HST loads in orbit day and the DM batteries and HST batteries (to the extent possible) will source the HST and DM loads in orbit night. In this mode, Science operations may or may not be possible depending on the DM load, DM SA load capability, the HST load, and the health of the HST batteries.

In the event that one or more SA3 taps are successful, the SA3 tap(s) could be used in a hybrid mode permitting limited science operation. The amount of science operation is determined by the number of

SA3 taps completed, the DM Load, the DM SA load capability, the HST load, and the health of the HST Batteries.

3.6 Structural Grounding:

The DM shall be structurally grounded to HST by less than or equal to 10 Milliohms. In the event that the P101 Umbilical is mated to the HST J101 receptacle, structural grounding is provided by two 12 AWG contacts in the Umbilical connected to two 8 AWG wires tied to the HST AB structure. In the event that the P101 receptacle fails to mate to HST J101, the DM will be contingency mated to the HST P105 and P106 Deployment Umbilicals. The P105 and P106 Umbilicals do not have structural ground contacts. Therefore an alternate contingency structural ground path shall be defined.

Careful consideration of the SA3 String return paths with respect to the DM-to-HST input power regulation method, power returns, and structural ground paths is required to ensure that undesirable ground loops are not formed. Ground loops shall be avoided to prevent elevated noise levels, structure currents, and vehicle body torques due to unbalanced electromagnetic reactions with the Earth's magnetic field.

The following two hypothetical examples highlight the subtleties of designing Battery Augmentation for HST. The first example uses an isolated return HST input power regulation method in which the HRV EPS returns are isolated from the HST EPS power input returns. The isolated return method was successfully used on the four HST Servicing Missions in which the Orbiter provided regulated external power to HST via the J101 Umbilical. The second example uses a commoned return HST input power regulation method in which the HRV EPS returns are commoned with the HST EPS power input returns.

3.6.1 Isolated Return Battery Augmentation

Figure 15 shows a hypothetical HRV, prior to docking with HST, with a Battery Augmentation design using isolated returns. The DM Single Point Ground (SPG) is active to provide an HRV structure return path. The EM and DM power bus and structure grounds are interconnected across the EM-DM separation plane. The HST Battery Augmentation regulator is off and the P101 isolation switch is open.

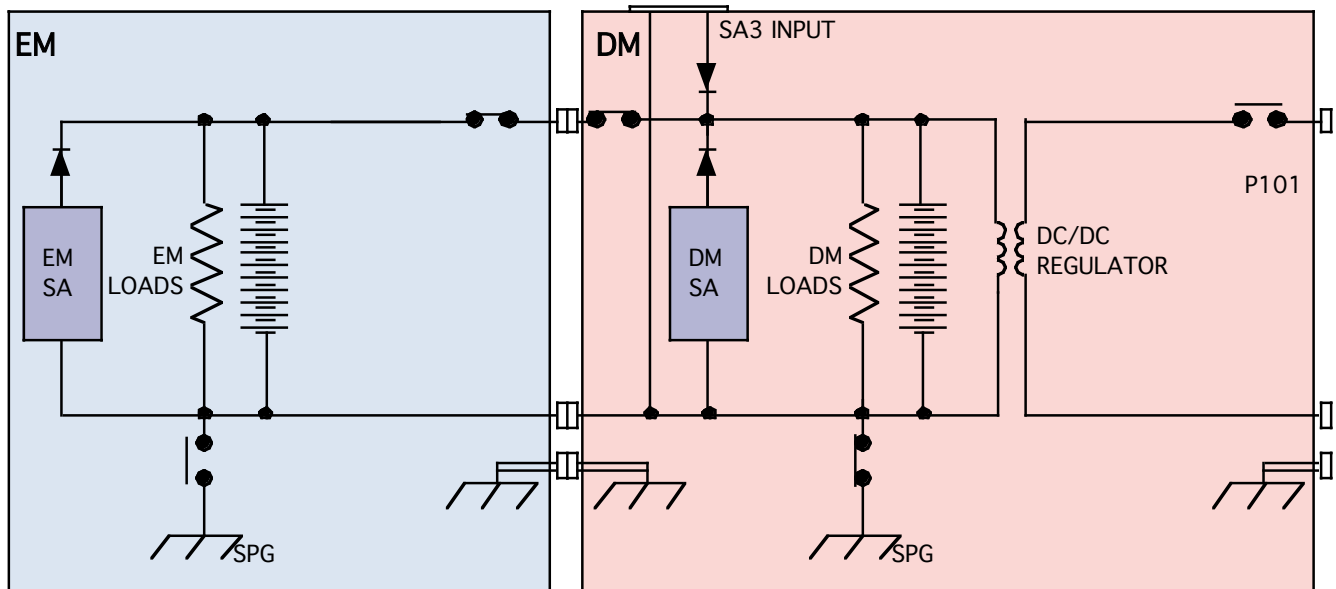


Figure 15, HRV Free-Flyer With Isolated HST Battery Augmentation

Figure 16 shows the hypothetical HRV docked to HST. The DM SPG remains closed to provide a structure return for the HRV EPS. HST's SPG provides the structure return for the HST EPS and the Battery Augmentation secondary. The EM and DM power bus and structure ground are interconnected across the EM-DM separation plane. The HRV structure is tied to HST structure via the P/J101 Umbilical. The SA3 P6A and P8A harnesses from both DBA2s have been successfully mated to the DM SA3 power input receptacles. The HST Battery Augmentation regulator is on and the P101 isolation switch is closed. Since the remaining SA3 harnesses (P5A and P7A) remain mated to the DBA2s and all of the SA3 SPA grouped String returns are commoned in the SA3 mast couplers (see Figure 5), two return paths are available for the SA3 String current returns. One path is through the add-on SA3 power tap harnessing to the DM EPS return. The other path is from the DM EPS return, through the DM SPG, across the P/J101 Umbilical, to the HST SPG, to the HST EPS return, to the SA3 return. The only way to remove the second path is to demate the remaining SA3 P5A and P7A harnesses from the DBA2s to break the return path or open the DM SPG switch. Opening the DM SPG switch is undesirable since a DM bus short to structure would be returned from the DM Chassis, across the P/J101 Umbilical, to the HST SPG, up through the HST DBA2, through the SA3 mast couplers, and back to the DM via the external power tap harnessing. This fault current path is undesirable due to the potentially high levels of fault current that may pass through the wiring in the SA3 system.

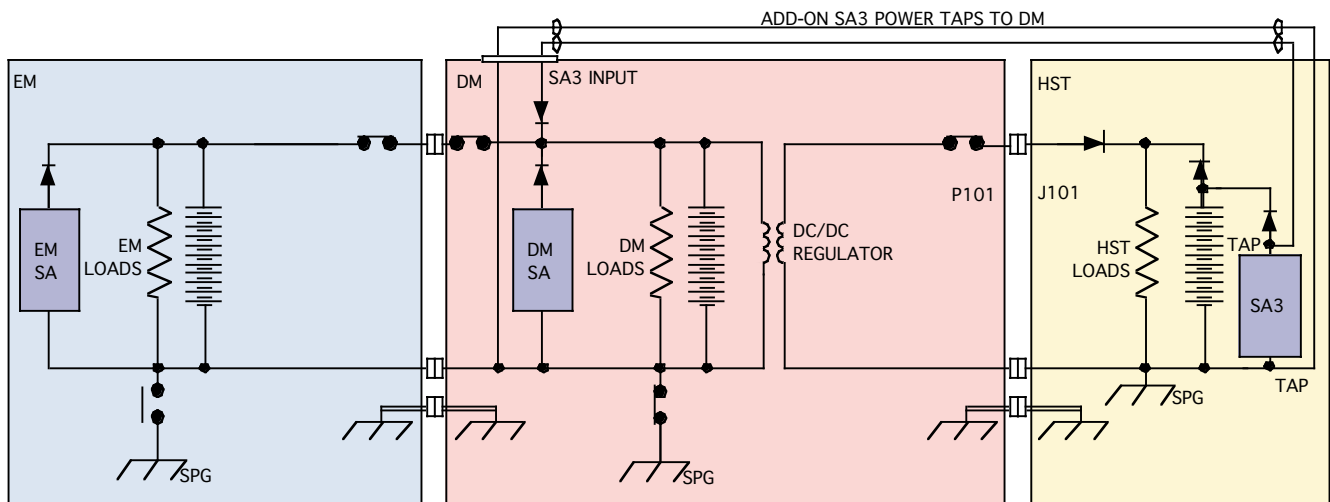


Figure 16, HRV Docked to HST, SA3 P6A and P8A Taps Completed With Isolated HST Battery Augmentation

Figure 17 shows the hypothetical HRV, where the P5A and P7A Harness connectors have been demated from the DBA2s to remove the second SA3 String return path.

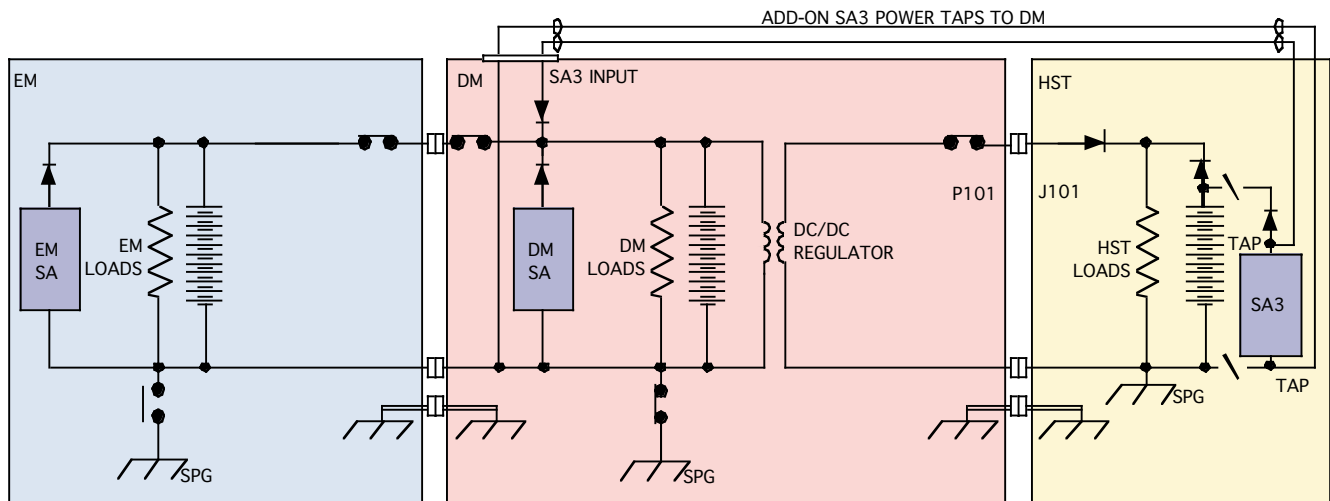


Figure 17, HRV Docked to HST, SA3 P6A and P8A Taps Completed, P5A and P7A Harnesses Demated, With Isolated HST Battery Augmentation

Figure 18 shows the hypothetical HRV with the EM jettisoned after completion of robotic servicing. The EM-DM EPS isolation switches are open and the EM SPG is closed to provide an EM structure return path.

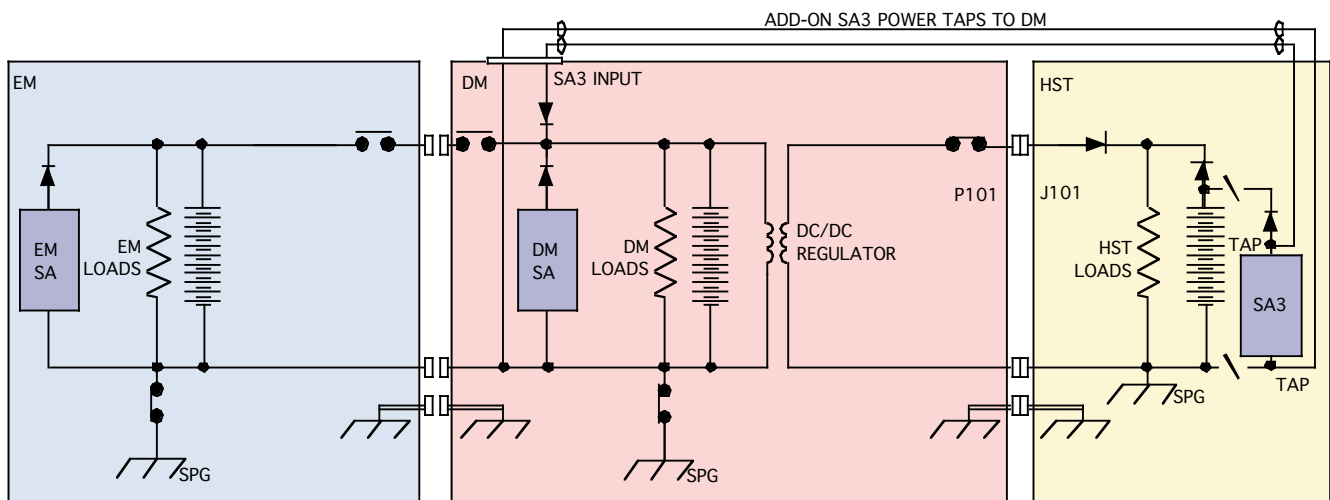


Figure 18, DM Docked to HST, EM Jettisoned, SA3 P6A and P8A Taps Completed, P5A and P7A Harnesses Demated, With Isolated HST Battery Augmentation

3.6.2 Commoned Return Battery Augmentation

Figure 19 shows a hypothetical HRV, prior to docking with HST, with a Battery Augmentation design using commoned returns. The EM SPG is active to provide an HRV structure return path. The EM and DM power bus and structure grounds are interconnected across the EM-DM separation plane. The HST Battery Augmentation regulator is off and the P101 isolation switch is open.

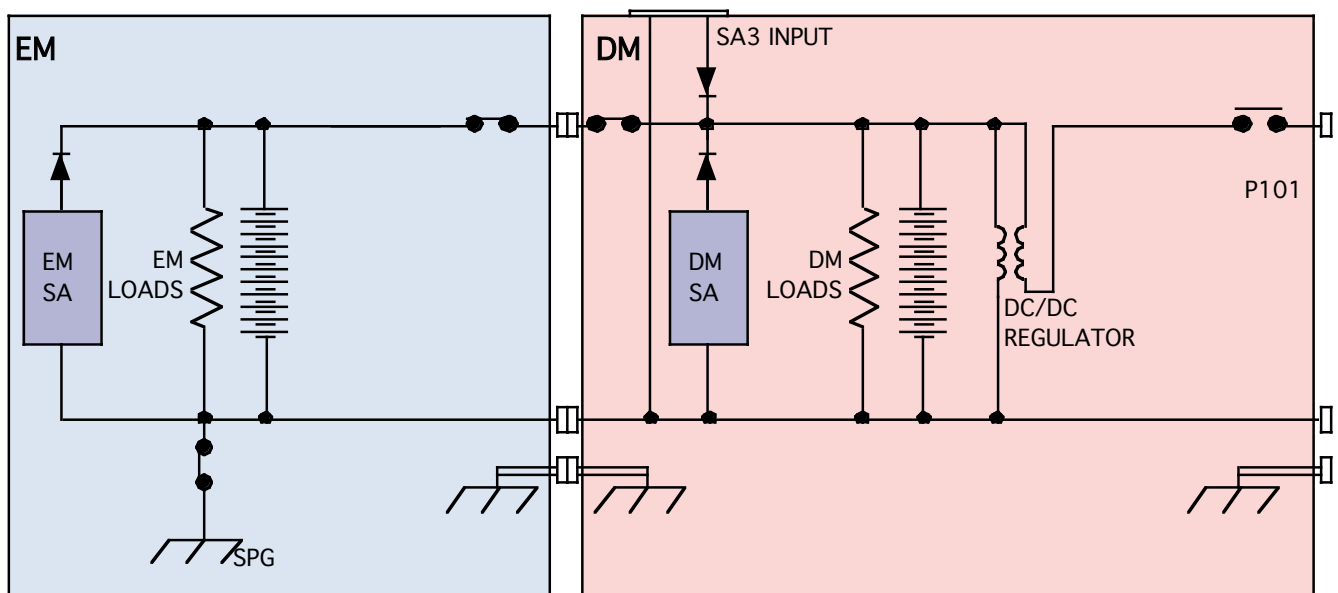


Figure 19, HRV Free-Flyer With Commoned Return HST Battery Augmentation

Figure 20 shows the hypothetical HRV docked to HST. The EM SPG is disconnected. HST's SPG provides the structure return for the HRV and HST EPS. The EM and DM power bus and structure ground are interconnected across the EM-DM separation plane. The HRV structure is tied to HST structure via the P/J101 Umbilical. The SA3 P6A and P8A harnesses from both DBA2s have been successfully mated to the DM SA3 power input receptacles. The HST Battery Augmentation regulator

is on and the P101 isolation switch is closed. Since the remaining SA3 harnesses (P5A and P7A) remain mated to the DBA2s and all of the SA3 SPA grouped String returns are commoned in the SA3 mast couplers (see Figure 5), two return paths are formed for the SA3 String returns. One path is through the add-on SA3 power tap harnessing return. The other path is from the commoned HRV-HST EPS returns to the SA3 return. The only way to remove the second path is to demate the remaining SA3 P5A and P7A harnesses from the DBA2s to break the return path.

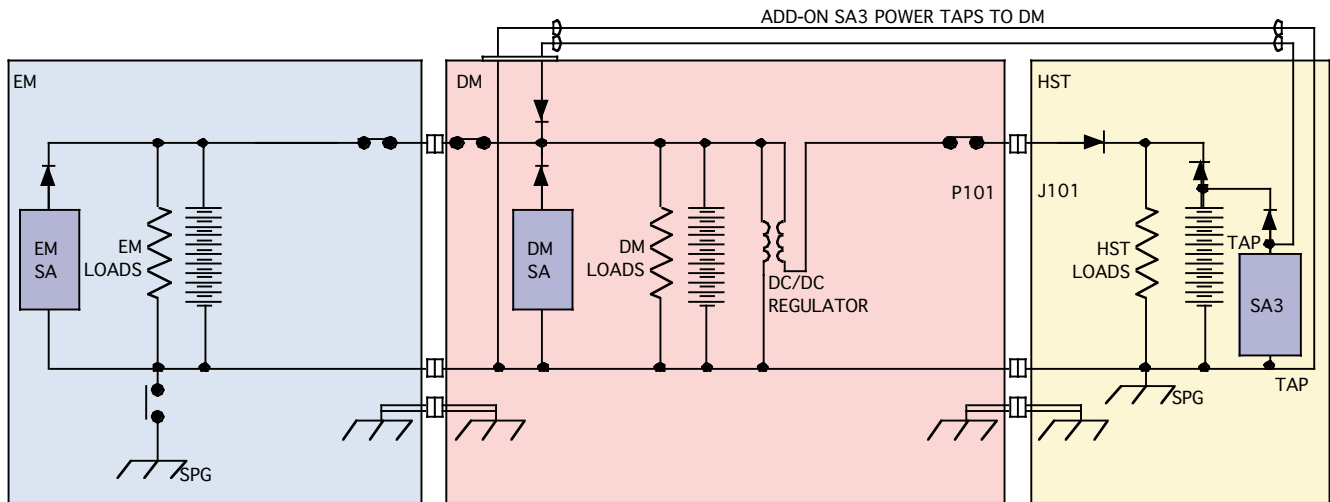


Figure 20, HRV Docked to HST, SA3 P6A and P8A Taps Completed With Commoned HST Battery Augmentation

Figure 21 shows the hypothetical HRV, where the P5A and P7A Harness connectors have been demated from the DBA2s to remove the second SA3 String return path.

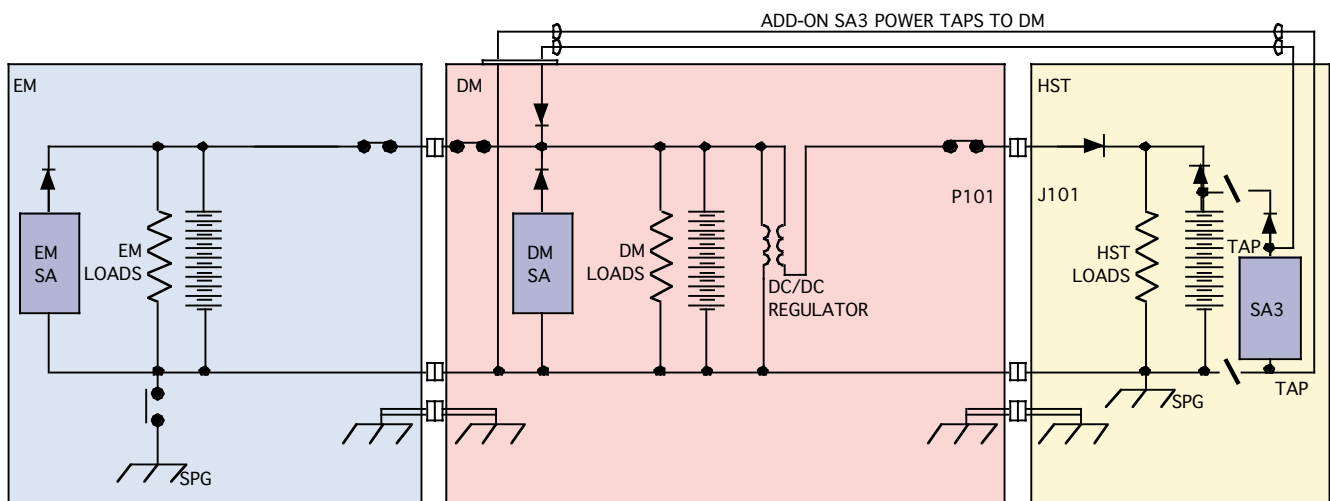


Figure 21, HRV Docked to HST, SA3 P6A and P8A Taps Completed, P5A and P7A Harnesses Demated, With Common Return HST Battery Augmentation

Figure 22 shows the hypothetical HRV with the EM jettisoned after completion of robotic servicing. The EM-DM EPS isolation switches are open and the EM SPG is closed to provide an EM structure return path.

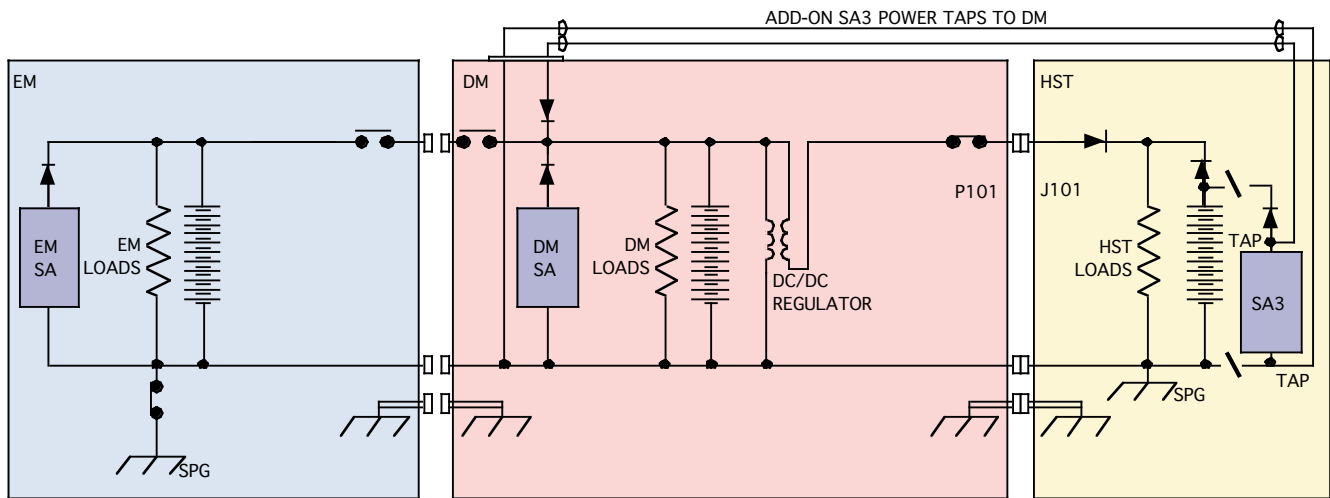


Figure 22, DM Docked to HST, EM Jettisoned, EM SPG Connected, SA3 P6A and P8A Taps Completed, P5A and P7A Harnesses Demated, With Commoned HST Battery Augmentation

3.6.3 Battery Augmentation with DBA2 P5A, P6A, P7A, and P8A Connectors Demated

In the previous two sections, it was hypothetically shown that undesired ground loops could be avoided by demating P5A, P6A, P7A, and P8A from both HST DBA2 units. However, this solution is not programmatically desirable for the following reasons:

- HST/DM 'Hybrid' Power System not possible. HST EPS system is no longer connected to the HST SA3 and thus the remaining life in HST batteries is forfeited.
- It is possible, due to on-orbit conditions and circumstances, that one or more of the HST DBA2 connectors may not be removed during servicing. This would result in undesired ground loops. In the hypothetical Isolated Return Battery Augmentation scheme presented above, this servicing anomaly could be compensated for by the opening of the SPG relay in the hypothetical DM module at the programmatic risk of future fault structure current incurring damage to the wiring in the HST SA3 path. The hypothetical Commoned Return Battery Augmentation scheme presented above has no contingency recourse for this type of servicing anomaly.